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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE June 12, 1997	3. REPORT TYPE AND DATES COVERED Final 11 May 92 - 31 Dec 96		
4. TITLE AND SUBTITLE Sequential Resonant Tunneling and Electric Field Effects in Semiconductor Superlattices		5. FUNDING NUMBERS DAAL03-92-G-0233		
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Michigan, Ann Arbor, MI 48109		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211		10. SPONSORING/MONITORING AGENCY REPORT NUMBER ARO 29923.15-PH		
11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.		12b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words)  This report focuses on mechanisms of negative-differential-conductance in weakly-coupled semiconductor superlattices and, in particular, on the phenomenon of sequential resonant tunneling leading to electric-field domains. Our approach involves a combination of various theoretical and experimental methods including time-resolved photoluminescence, Raman scattering and near-field-optical microscopy. A nearly complete understanding of the domain process has emerged. Specifically, a phase diagram has been established and the various parameters which control transport behavior have been identified. In photoexcited and intentionally doped superlattices, static domains dominate at high carrier concentrations while oscillations occur in a narrow density region above the regime of the quantum-confined Stark effect. Doped, although not photoexcited structures exhibit sustained GHz oscillations. The relevance of these findings to Bloch oscillations is discussed.  DTIC QUALITY INSPECTED 4				
14. SUBJECT TERMS resonant tunneling, superlattices, quantum-well structures, negative-differential-conductance, electric-field domains, time-resolved photoluminescence, Raman scattering, self-sustained oscillations, intersubband excitations, Gunn effect.		15. NUMBER OF PAGES nine (9)		
		16. PRICE CODE		
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

# SEQUENTIAL RESONANT TUNNELING AND ELECTRIC FIELD EFFECTS IN SEMICONDUCTOR SUPERLATTICES

## FINAL REPORT

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June 12, 1997

U. S. Army Research Office

Contract No. DAAL03-92-G-0233

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## FOREWORD

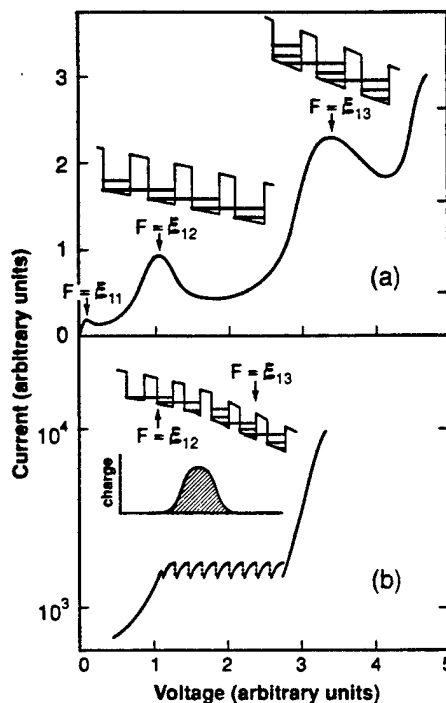
In this report, we present a brief account of research findings for projects supported by the ARO Contract No. DAAL03-92-G-0233 [Amount: \$262,500, for the period May 11, 1992 through December 31, 1996]. Other than the PI, the work involved two graduate students and one undergraduate student. Some of the projects benefited from the participation of Dr. L. Schrottke, a visiting DAAD scholar from the Paul Drude Institut, Berlin (Germany) and Dr. G. Ambrazevičius, a Soros Foundation Fellow from the Institute of Semiconductor Physics, Vilnius (Lithuania).

### A. ELECTRIC FIELD DOMAINS IN QUANTUM-WELL STRUCTURES

Central to the transport behavior of semiconductor superlattices (SLs) is the question of the mechanisms of negative-differential-conductance and associated instabilities [1,2]. This problem bears on phenomena as diverse as Bloch oscillations [3] and Wannier-Stark ladders [4] as well as on various aspects of nonlinear dynamics [5] and resonant tunneling [6-8]. A related but distinct question is that of the transitions between different transport modes. As it has been known for quite some time, SLs may spontaneously break into regions referred to as electric-field domains (EFD) so that the field is not uniform but piecewise constant across the sample [9-16]. However, the nature of the instability and that of the parameters which control the transition have remained largely unexplained until recently. The ARO program directed by the PI focused on this problem. His approach involved a combination of various theoretical and experimental methods including time-resolved photoluminescence (PL), Raman scattering and near-field-optical microscopy. As a result of these efforts and collaborations with the group of L. Bonilla at the *Universidad Carlos III* (Madrid, Spain) and that of K. Ploog at the *Paul Drude Institut* (Berlin, Germany), a nearly complete understanding of EFD behavior has emerged. A summary of major research findings is given below.

Domains are specific to the quantum-well (QW) regime of small miniband widths. For weakly-coupled QW structures, transport is dominated by sequential resonant tunneling [6-8]. The main regimes are illustrated in Fig. 1. At low carrier densities, the  $I$ - $V$  response is of the form shown in Fig. 1 (a) with maxima at fields  $\mathcal{E}_{ij}$  ( $i, j \geq 1$ ) corresponding to the neighboring-well alignment of the  $i$ th- and  $j$ th- subbands [8]. The trace in Fig. 1 (b), analogous to the conductance data reported by

**Fig. 1** - Schematic traces corresponding to (a) uniform-field (low-density) and (b) domain regimes (high density). The current maxima in (a) are due to tunneling involving the level alignment shown in the figure. In (b), the ratchet-like structure reflects the motion of the domain wall by one SL period.



Esaki and Chang [7] in 1974, reflects the presence of *microscopic* EFD [9-16]. In the course of our studies, it has become clear that the dependence shown in (b) corresponds to the high-density limit. In our time-domain PL work, we investigated the transition between the EFD and the uniform-field regime by monitoring the time behavior of a photoexcited QW-system as it evolves from (a) to (b). For this, the photoexcitation was turned on and off by switching a Pockels cell placed between crossed polarizers; our set-up gives step-like profiles with rise times of  $\approx 5$  ns at a repetition rate of 3.5 kHz. The data reproduced in Fig. 2 obtained in this manner show a single PL-feature at  $t = 0$  which splits into two peaks corresponding to the two domains. Here, the most important point is that the peaks (as well as the photocurrent) exhibit *damped* oscillations. As shown in the inset, the fundamental frequency vs.  $V$  contains minima and discontinuities which appear to correlate with those of the steady-state photocurrent; the decay time ( $\approx 0.2$ - $0.5$   $\mu$ s) shows a similar trend.

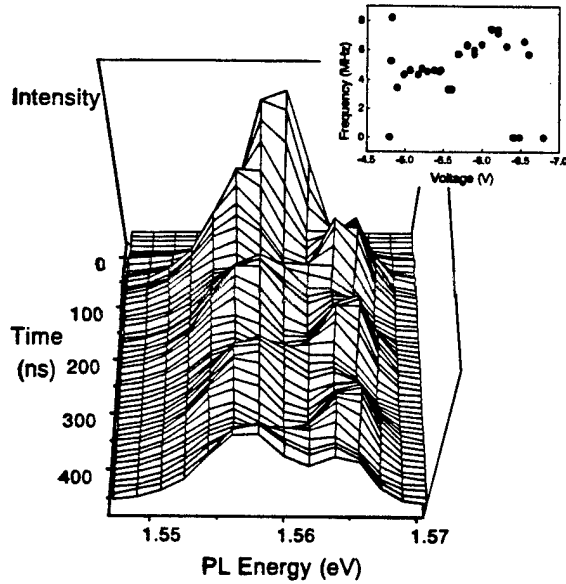


Fig. 2 - Experimental time-resolved PL for a photoexcited structure at  $V = -6.21V$ . Spectra are given at intervals of 10 ns. The oscillating peaks correspond to the two domains. The  $V$ -dependence of the fundamental oscillation frequency is shown in the inset.

Studies of the transport equations reveal transient oscillations, as in the PL experiments, in the range shown in Fig. 3. Furthermore, one finds stationary solutions which, depending on the parameters, have either one or three fixed points [16]. The latter case exists only for voltages between two current maxima and it corresponds to EFD. Using linear stability analyses, we determined the region shown in Fig. 3 for which EFD (uniform-field) is stable (unstable). In general, there are many solutions with a similar field profile, but with the wall displaced by one or more wells. Consistent with experiments, this gives rise to hysteresis and flat, ratchet-like traces similar to that in Fig. 1 (b).

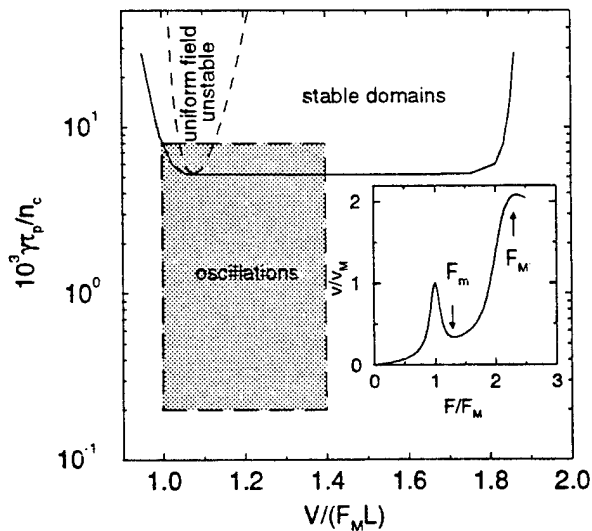


Fig. 3 - Theoretical phase diagram for a photoexcited system;  $\gamma$  is the photogeneration rate and  $V$  is the voltage. The shaded region denotes the range of damped domain oscillations. Inset: The normalized field dependence of the carrier velocity used as input in the calculations.

Results of Raman scattering from intersubband excitations for a photoexcited sample are shown in Fig. 4. As for PL [12], the spectra reveal two intersubband peaks in the EFD range. A significant feature of the data is that one can gain information on the magnitude of the charge by comparing spin- and charge-density spectra.

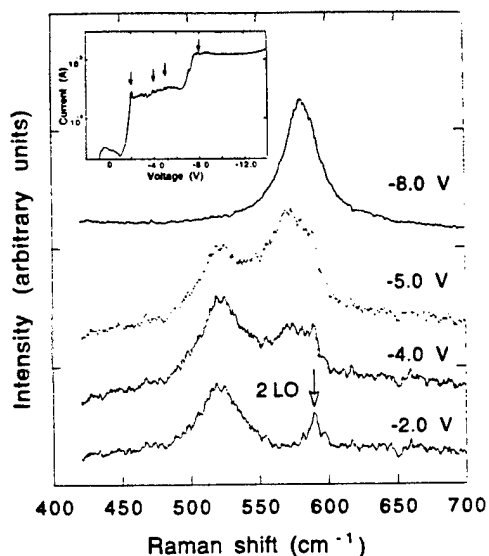


Fig. 4 - Raman spectra of a photoexcited *p-i-n* SL showing intersubband excitations. Doublets at -4V and -5V reflect the two domains in the structure. The peak labeled 2LO is due to scattering by two zone-center longitudinal optical phonons. Inset: current vs. voltage; arrows denote voltages corresponding to those of the spectra.

One of the most exciting results of this program was the discovery of self-sustained oscillations in *doped* QW-structures (we emphasize that the oscillations shown by *photoexcited* structures eventually die-out). Fig. 5 summarizes data for two different samples. The observation of oscillations suggests a link between domain instabilities and the bulk Gunn effect. However, there is an important difference in that quantum-wells allow one to tune the position and the number of tunneling maxima over a wide range by an appropriate change of growth parameters (for Gunn diodes, the important variables are mainly the sample length and the doping). While higher frequencies can possibly be achieved by careful control of the SL parameters, it remains to be seen that the instability can lead to frequencies beyond the GHz range. In this context, we notice that - with decreasing tunneling time - one would eventually approach the regime of strongly coupled samples (wide miniband-width) associated with Bloch oscillations. While our oscillations are very different in nature, we speculate that the Bloch frequency is the limiting frequency for domain instabilities.

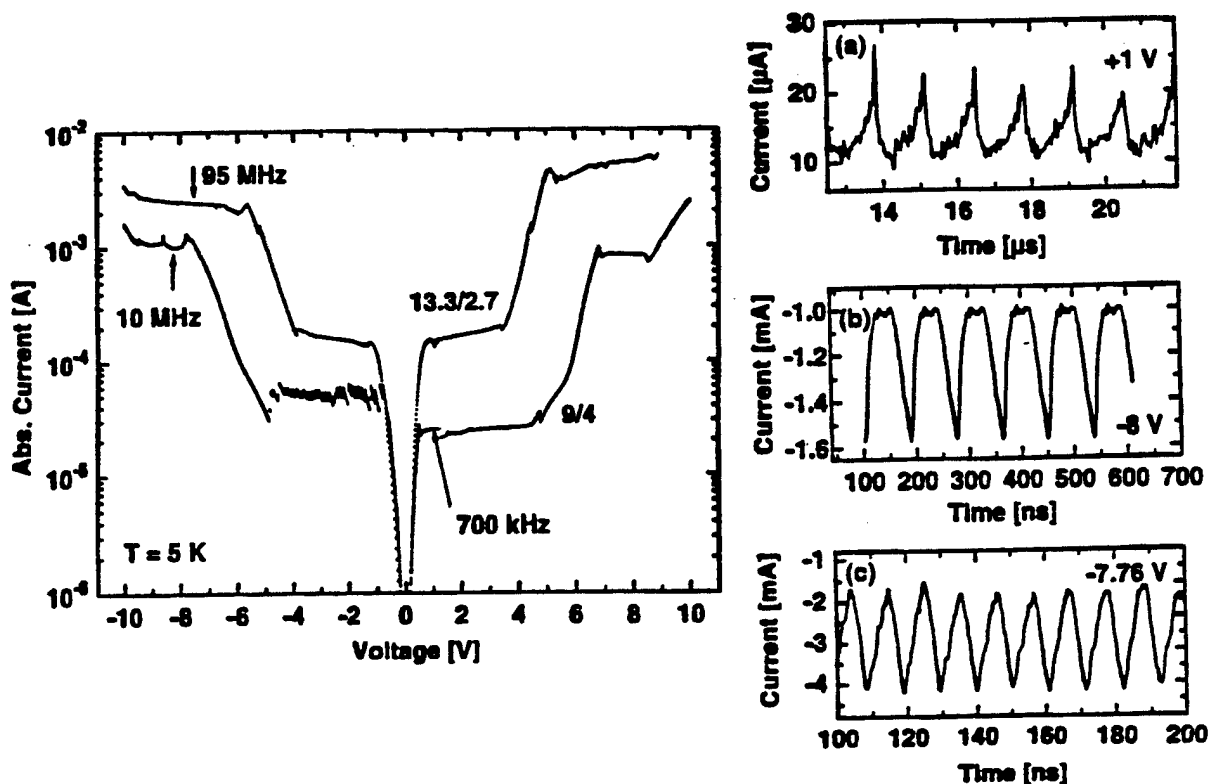


Fig. 5 - (left)  $I$ - $V$  characteristics of  $n$ -doped superlattices  $A$ : 9 nm GaAs-4.0 nm AlAs and  $B$ : 13.3 nm GaAs-2.7 nm AlAs; (right) Current vs. time. Data for sample  $A$  are shown in (a) and (b), and for  $B$  in (c).

## B. OTHER RESULTS

A few small projects unrelated to EFD research were supported by and completed during the duration of the current award. From this group, one can single out due to their importance (i) the Raman work on GaN and (ii) our theoretical studies on rotational anomalies of mesoscopic conducting rings. In the experiments on GaN films grown by MBE, we were able for the first time to obtain second-order phonon spectra. Our work on mesoscopic systems showed that, in rings threaded by a magnetic flux, the electron moment of inertia  $I_e$  exhibits a periodic pattern with maxima at  $\Phi_0 = hc/e$  or  $\Phi_0/2$  [modulo  $\Phi_0$ ] depending on the number of electrons. For slowly rotating rings, we

found that  $I_c$  diverges in the limit of weak disorder. The rotational anomalies rely on the same interference mechanism responsible for persistent currents and the Aharonov-Bohm effect. More recently, we proved a simple relation between the conductivity and  $I_c$ , and showed that rotating rings carry a magnetic moment analogous to the London moment of superconductors.

## REFERENCES

- [1] L. Esaki and R. Tsu, IBM J. Res. Dev. **14**, 61 (1970).
- [2] A. Sibille *et al.*, Phys. Rev. Lett. **64**, 52 (1990); X. L. Lei, N. J. M. Horing and H. L. Cui, Phys. Rev. Lett. **66**, 3277 (1991).
- [3] See, *e. g.*, C. Waschke *et al.*, Phys. Rev. Lett. **70**, 3319 (1993).
- [4] J. Bleuse, G. Bastard and P. Voisin, Phys. Rev. Lett. **60**, 220 (1988); E. E. Mendez, F. Agulló-Rueda and J. M. Hong, Phys. Rev. Lett. **60**, 2426 (1988); K. H. Schmidt *et al.*, Phys. Rev. Lett. **72**, 2769 (1994).
- [5] See: *Proceedings of the NATO Advanced Research Workshop on Negative Differential Resistance and Instabilities in 2-D Semiconductors*, ed. by N. Balkan, B. K. Ridley and A. J. Vickers, NATO Advanced Study Institutes, Ser. B, Vol. 307 (Plenum, New York, 1992).
- [6] R. F. Kazarinov and R. A. Suris, Fiz. Tekh. Poluprov. **6**, 148 (1972) [Sov. Phys. Semicond. **6**, 120 (1972)].
- [7] L. Esaki and L. L. Chang, Phys. Rev. Lett. **33**, 495 (1974).
- [8] F. Capasso, K. Mohammed and A. Y. Cho, Appl. Phys. Lett. **48**, 478 (1986).
- [9] K. K. Choi *et al.*, Phys. Rev. B **38**, 12362 (1988), and references therein.
- [10] T. H. H. Vuong, D. C. Tsui and W. T. Tsang, Appl. Phys. Lett. **52**, 981 (1988).
- [11] M. Helm *et al.*, Phys. Rev. Lett. **63**, 74 (1989).
- [12] H. T. Grahn *et al.*, Phys. Rev. Lett. **67**, 1618 (1991).
- [13] A. Shakouri *et al.*, Appl. Phys. Lett. **63**, 1101 (1993).
- [14] S. H. Kwok *et al.*, Phys. Rev. B **50**, 2007 (1994).
- [15] F. Prengel, A. Wacker and E. Schöll, Phys. Rev. B **50**, 1705 (1994).
- [16] L. L. Bonilla, *et al.*, Phys. Rev. B **50**, 8644 (1994).



## C. PUBLICATIONS UNDER ARO SPONSORSHIP

### JOURNALS

1. "Nonlinear Optical Spectroscopy in GaAs: Magnetic Freezeout of Excitons." M. Jiang, H. Wang, R. Merlin, M. Cardona and D. G. Steel, Phys. Rev. B (Rapid Communications) **48**, 15476-15479 (1993).
2. "Rotational Anomalies of Mesoscopic Rings." R. Merlin, Phys. Lett. A **181**, 421-423 (1993).
3. "Growth of Electric Field Domains in Quantum-Well Structures: Correlation with Intersubband Raman Scattering." S. Murugkar, S. H. Kwok, G. Ambrazevičius, H. T. Grahn, K. Ploog and R. Merlin, Phys. Rev. B (Rapid Communications) **49**, 16849-16851 (1994).
4. "Electric Field Domains in Semiconductor Superlattices: Resonant or Non-resonant Tunneling?" S. H. Kwok, R. Merlin, H. T. Grahn and K. Ploog, Phys. Rev. B (Rapid Communications) **50**, 2007-2010 (1994).
5. "Domain Wall Kinetics and Tunneling-Induced Instabilities in Superlattices." S. H. Kwok, T. B. Norris, L. L. Bonilla, J. Galán, J. A. Cuesta, F. C. Martínez, J. M. Molera, H. T. Grahn, K. Ploog and R. Merlin, Phys. Rev. B **51**, 10171-10174 (1995).
6. "Non-resonant Carrier Transport through High-Field Domains in Semiconductor Superlattices." S. H. Kwok, H. T. Grahn, M. Ramsteiner, K. Ploog, F. Prengel, A. Wacker, E. Schöll, S. Murugkar and R. Merlin, Phys. Rev. B **51**, 9943-9951 (1995).
7. "Self-Oscillations of Domains in Doped GaAs-AlAs Superlattices." J. Kastrup, R. Klann, H. T. Grahn, K. Ploog, L.L. Bonilla, J. Galán, M. Kindelan, M. Moscoso and R. Merlin, Phys. Rev. B **52**, 13761-13764 (1995).
8. "Second Order Raman Spectroscopy of the Wurtzite Form of GaN." S. Murugkar, R. Merlin, A. Botchkarev, A. Salvador and H. Morkoç, J. Appl. Phys. (Communications) **77**, 6042-6043 (1995).
9. "Persistent Magnetic Moment of Rotating Mesoscopic Rings and Cylinders." A. G. Rojo and R. Merlin, Phys. Rev. B **54**, 1877-1879 (1996).

### CONFERENCE PROCEEDINGS

1. "Enhanced Linear Electro-optic Anisotropy in GaAs Quantum Wells," S. H. Kwok, H. T. Grahn, K. Ploog and R. Merlin, in *Optical Phenomena in Semiconductor Structures of Reduced Dimensions*, ed. by D. J. Lockwood and A. Pinczuk (Kluwer Academic Publishers, Dordrecht, 1993), pp. 239-245; invited paper at the NATO Advanced Research Workshop on Frontiers of Optical Phenomena in Semiconductor Structures of Reduced Dimensions, 1992, Yountville, CA.

2. "Dynamics of Resonant Tunneling Domains in Superlattices: Theory and Experiments." R. Merlin, S. H. Kwok, T. B. Norris, H. T. Grahn, K. Ploog, L. L. Bonilla, J. Galán, J. A. Cuesta, F. C. Martínez and J. M. Molera, in *The Physics of Semiconductors*, Vol. 2, ed. by D. J. Lockwood (World Scientific, Singapore, 1995), pp. 1039-1042; presented at the 22th International Conference on the Physics of Semiconductors, 1994, Vancouver, Canada.
3. "Correlation Between Intersubband Raman Scattering and Electric-Field Domains in Quantum-Well Structures." S. Murugkar, R. Merlin, S. H. Kwok, H. T. Grahn and R. Hey, *Solid State Electron.* **40**, 153-155 (1996); presented at the Seventh International Conference on Modulated Semiconductor Structures, 1995, Madrid, Spain.
4. "Oscillating Electric Field Domains in GaAs-AlAs Superlattices." J. Kastrup, H. T. Grahn, K. Ploog and R. Merlin, *Solid State Electron.* **40**, 157-160 (1996); presented at the Seventh International Conference on Modulated Semiconductor Structures, 1995, Madrid, Spain.

#### OTHER CONTRIBUTIONS

1. "Raman Scattering by Plasmons in Fibonacci Superlattices." R. Merlin, J. P. Valladares, A. Pinczuk, A. C. Gossard and J. H. English, in *A Festschrift Issue to Pay Tribute to Professor Elias Burstein* (invited contribution), *Solid State Commun.* **84**, 87-89 (1992).
2. "Raman Spectra of  $\text{In}_x\text{Ga}_{1-x}\text{As}$ ." R. Merlin, in *Properties of Lattice-Matched and Strained InGaAs* edited by P. K. Bhattacharya (Electronic Materials Information Service, London, 1993), EMIS Datareviews Series No. 8, Ch. 7.2, pp. 192-198.
3. "Raman Scattering by Surface-Avoiding Acoustic Phonons in Semi-Infinite Superlattices." R. Merlin, in *Festschrift in honor of Manuel Cardona's 60th birthday* (invited contribution), ed. K. Syassen, M. Stutzmann, C. Thomsen and J. Zegenhagen, *Phil. Mag. B* **70**, 761-766 (1994).

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